

ELECTRO-OSMOTIC PULSE TECHNOLOGY: A NOVEL SOLUTION TO SEVERE WATER INTRUSION PROBLEMS IN EARTH COVERED MAGAZINES

Orange S. Marshall, Jr.*, Michael K. McInerney, Sean Morefield and Vincent F. Hock

U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory
Champaign, IL 61822

ABSTRACT

The earth covered magazines (ECMs) at many Army installations have severe moisture intrusion problems. This water intrusion causes deterioration and corrosion of ammunition and equipment within the ECMs, making many types of ordinance unusable, including sensitive munitions with sophisticated electronic fusing and missiles. The Engineer Research and Development Center Construction Engineering Laboratory (ERDC-CERL) was contacted by the Ft. A.P. Hill DPW to assist in solving the severe water intrusion problem in steel arch ECMs at that location. To address the problem ERDC-CERL recommended installing Electro-Osmotic Pulse (EOP). Prior to installing the EOP system in an ECM, several safety concerns needed to be addressed, such as the interaction of the EOP system with the ECM lightning protection system, the potential for hydrogen gas generation by the EOP system, and the effects on munitions. To evaluate those concerns, ERDC-CERL performed laboratory testing of a model steel arch ECM with an EOP system installed in it. Scale model results were positive and testing in a full scale ECM at Fort A.P. Hill is proceeding.

1. BACKGROUND

Fort A.P. Hill contacted the Engineer Research and Development Center Construction Engineering Laboratory (ERDC-CERL) with a water intrusion problem in the steel arch earth covered magazines (ECMs) constructed in the 1950s. A visual examination of the problem by ERDC-CERL revealed that the majority of the water was entering through the concrete walls, rather than through joints and cracks in the structures. The situation was deemed ideal for ElectroOsmotic Pulse (EOP) technology. A Return-on-Investment (ROI) study concluded that EOP is also the most cost effective solution.

ERDC-CERL submitted a Research and Development proposal under the DoD Facilities

Corrosion Protection and Control Program to implement EOP in the ECMs. The project was funded jointly by the Office of the Secretary of Defense and the Army Installation Management Agency to conduct the necessary developmental Research and Development for ECM implementation and demonstrate the EOP technology at Fort A.P. Hill.

EOP technology is based on the principle of electro-osmosis; the movement of a liquid through a porous media under the influence of an external electric field. Pulsed electro-osmosis technology was developed for control of water intrusion within concrete and masonry structures. EOP uses two sets of electrodes. One set is embedded just below the surface of the concrete walls or floors; the other is placed either in the surrounding soil or if the wall is thick, deep within the concrete wall. A pulsing DC voltage (Fig. 1) is applied between the electrodes to produce an electric field in the concrete, which moves water from the dry side (interior) toward the wet side (exterior), preventing moisture from reaching the interior surface of the concrete.

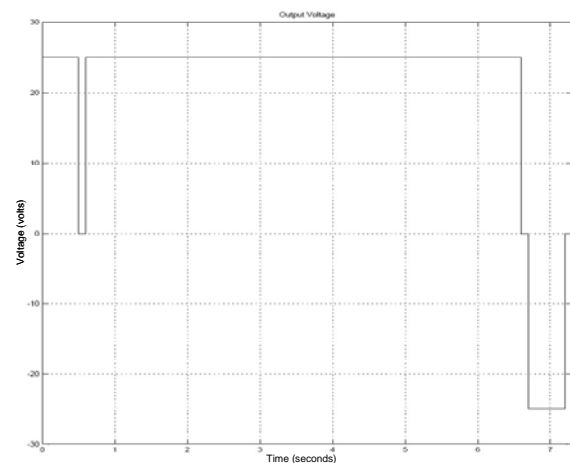


Figure 1: Typical EOP system pulse wave form.

Figure 2 is a sketch showing this process. A positive electrical pulse causes cations (e.g., Ca^{++}) with associated water molecules to move from the dry side (anode) towards the wet side (cathode)

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against the direction of flow induced by the hydraulic gradient, thus preventing water penetration through a buried or submerged concrete structure. Prior studies of EOP technology to assess the feasibility and cost effectiveness of this technology in comparison with conventional dampness mitigation techniques on selected concrete structures concluded that significant first cost savings of over 50% can be realized using EOP technology (Hock, 2005).

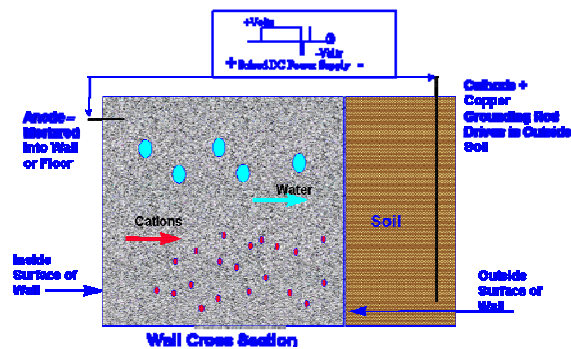


Figure 2: Sketch of EOP process.

2. OBJECTIVE

There were several safety issues that required evaluation before the EOP systems could be installed in the steel arch earth covered magazines (ECMs) at Fort A.P. Hill. Laboratory testing of a model earth covered magazine and full scale testing was performed to evaluate the following potential hazards:

- determine if there is any potential of sparking from the EOP system,
- evaluate the EOP system effects on the lightning protection systems installed in an ECM,
- optimize cathode locations in order to minimize impact on the existing ECM grounding systems,
- determine the potential for and quantify any potential generation of hydrogen gas, and
- determine the effects of DC electrical current induced by the EOP system in the concrete floors on metallic pallets placed on the floor inside the structure.

3. APPROACH

A scale model of a steel arch earth covered ammunition storage magazine was constructed and tested in the laboratory. The model had an EOP system installed similar to the planned design for the full scale magazines at Fort A.P. Hill. The model included the ECM lightning protection and grounding

systems. The model was buried in a laboratory test bed using a sandy clay backfill. The backfill was kept damp during the testing period. The EOP design was modified based on the test results and a system was installed in a full scale ECM at Fort A.P. Hill. Testing was conducted on the EOP system in the full scale ECM and data compared with results from the model's laboratory tests.

4. MODEL CONSTRUCTION

A simplified scale model ECM was constructed based on the section plans of the ECMs at Fort A.P. Hill (Fig. 3). A single ground loop and a single air terminal at the rear of the model were installed as part of the system. The ECMs at Fort A.P. Hill have a double grounding ring installed that surrounds the entire ECM. Scaling limitations prevented installation of the double ring system used in the actual construction. When scaled, the rings of a double ring ground system would have been so close together as to equate to a single ring. For the purposes of these tests a single ring ground of bare 12 gauge copper wire was considered adequate.

Figure 3 is a photograph of the assembled ECM model used for laboratory testing.



Figure 3: Laboratory scale model of ECM.

The base and walls of the model were constructed from concrete paving blocks, 1½ inches thick, and the roof from galvanized roof flashing. To simulate existing waterproofing, standard duct tape was applied to the roof section with approximately 1/16-in. gap between strips. The roof was attached to the walls using galvanized steel angles. The angles were held in place using bolts. The bolts went through the angles, the side walls and the base, and were secured with nuts. The front and rear walls were attached by pinning them to the floor section; using concrete screws to secure them to the side

walls; and connecting them at the apex with a ¼ in. threaded rod to hold them tight to the steel arch.

Prior to assembling the model, grooves were cut in the floor and back wall sections for placement of anodes. The anodes were embedded in a cementitious grout, and the same grout was used during assembly as a mortar between the wall sections and the floor section. After curing for 24 hours, the assembly was placed in 2 inches of standing water for four days to completely saturate the concrete. Each anode segment in the floor was instrumented to monitor the current. Concrete moisture measurements were made using probes embedded in the floor section at three locations and a commercially available moisture meter from Protimeter.

Leads to monitor voltage at the four corners of the steel arch were attached to screws that secured the steel arch to the angle iron. A lead wire ran from the angle iron to the ground ring (Fig. 3) on each side of the model. A rubber hose was attached to the floor section near one of the screws in order to measure the steel electric potential in the concrete using a copper-copper sulfate half-cell. (The standard method of measuring steel potential in concrete is to place a copper-copper sulfate half-cell on the concrete surface nearest to the steel and measure the voltage. Since the model was covered in clay, the concrete surface was not accessible. The hose was installed to provide a way to make electrical contact with the concrete from outside the clay. The hose was filled with tap water, which was electrically conductive, and the half-cell was placed in the water.)



Figure 4: Scale model ECM with earth covering.

Before placing soil in the test bed, a wire mesh was laid on the bottom to act as an earth ground for the lightning protection system. Figure 4 shows the test bed with the wire mesh and earth covering in place. The copper wire, shown in the soil in figure 3,

forms the ground ring, the chicken wire mesh represents the earth ground and the metal cylindrical structure models the metal roof of the actual structure. The blue insulated wire is the electrical connection between the metal building member and the ground ring. The vertical copper wire (upper right in figure 4) is a part of the lightning protection system. The completed structure was covered with earth (i.e., sandy clay).

5. MODEL TESTING

The ECM model was subjected to a variety of tests with an installed EOP system in order to measure the potential for creating an unsafe condition in a possibly explosive environment.

5.1 Sparking Potential Evaluation

Electrical potentials were monitored on the steel arch at the four corners and the ceiling. Any build-up of charge, which would be indicated by a voltage increase, could provide potential for a spark.

Potential measurements were taken using a Fluke digital multimeter. The potential was measured between the two screws on each corner of the steel arch (i.e. left, right, front, and back). No potential differences were detected between any of these points throughout the testing period.

If a charge had built up, special circuitry could be incorporated into the EOP system controller to prevent charge accumulation on the steel arch.

5.2 Lightning Protection System Evaluation

After the EOP system was running at steady state (about five days), the ground system was monitored to determine the degree of coupling between the EOP system and the lightning protection system.

The “lightning” simulation was produced by driving a Kepco Model BOP50-4M Bipolar operational power supply/amplifier with a repetitive pulse from a Wavetek Model 147 HF Sweep Generator. Signals were monitored using a 1X/10X voltage probe, a high voltage differential probe, and a Tektronix P6021 current probe (in combination with a Type 134 probe amplifier) and recorded with a Tektronix TDS 5104 Digital Oscilloscope. Approximately two amps were injected into the “lightning rod.”

An initial voltage measurement was made on the EOP source being applied to the model EOP system (total voltage between the anodes and cathodes). This reading was taken with a high voltage differential probe. A second voltage reading was taken between the lightning rod and the earth ground to determine the degree of coupling between the two systems. The results are shown in figure 5. The ratio of the peak magnitudes of the signal measured on the lightning rod system to that applied by the EOP system is miniscule, approximately 0.004.

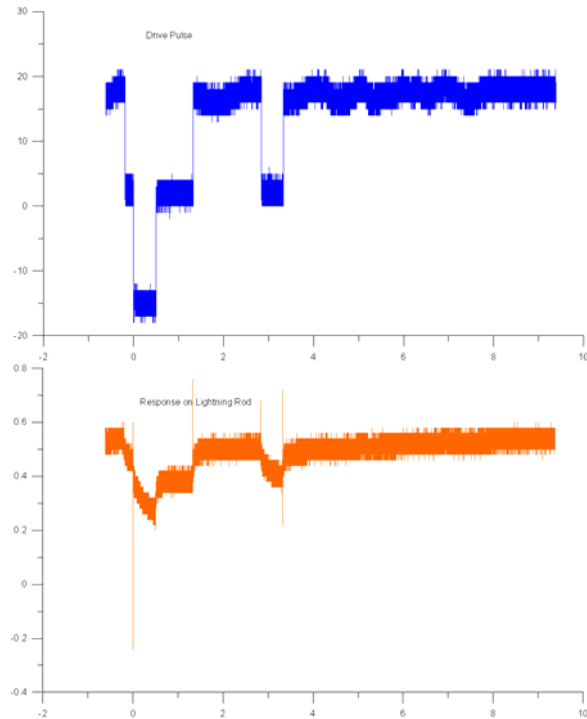


Figure 5: Voltage between the lightning rod and earth ground.

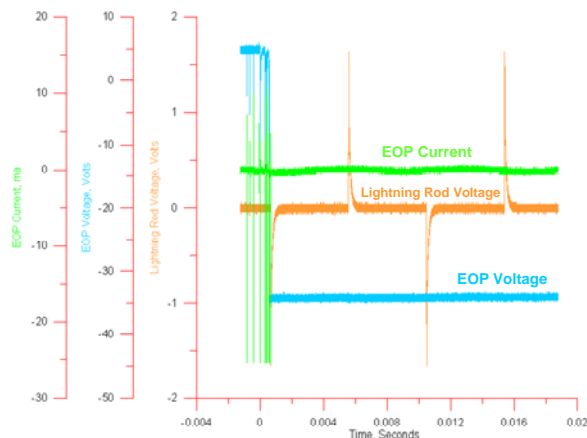


Figure 6: EOP system voltage and current response to voltage spikes on the lightning rod.

Figure 6 shows the applied voltage signal and the measured EOP voltage and current. It can be seen that at the scale factors necessary to monitor these signals, there is no detectable response on the EOP signal.

5.3 Cathode Placement Evaluation

To minimize impact on the existing grounding system, yet maintain EOP system efficiency, the EOP cathode placement was evaluated. It was not clear whether the EOP cathodes should be placed inside the ground ring or outside, or if it made any difference. Tests to determine cathode placement influence on the grounding system were conducted by monitoring potentials on the ground ring with several cathode placements. EOP system efficiency was evaluated by monitoring the current in the anode and cathode circuits.

The potential was measured between the ground ring and three other positions including the wire mesh (earth ground), the anodes, and the cathodes. The potential between the ground ring and the earth ground did not change whether the cathodes were placed inside or outside of the ground ring (Fig. 7). It was always less than 1 Volt.

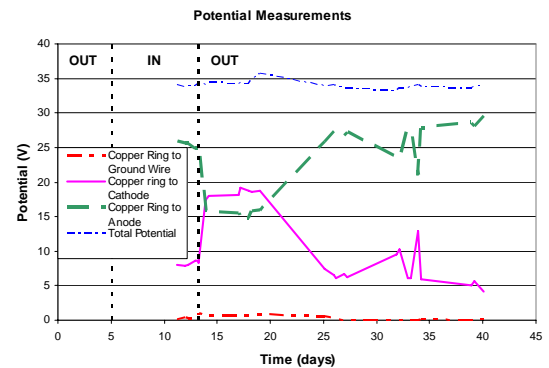


Figure 7: Plot of potential vs. time for different cathode placements; INSIDE and OUTSIDE the ground ring.

The potential between the ground ring and the cathodes increased when the cathodes were moved from inside the ring to the outside. The potential between the ground ring and the anodes decreased when the cathodes were moved from inside to outside. Total potential always equaled the power supply voltage, as one would expect since the ground ring is acting as a voltage probe located between the anodes the cathodes.

The magnitude and distribution of current in the anode and cathode circuits is a measure of EOP system efficiency. The magnitudes of the anode currents should be as close to the design value (in mA/foot) without exceeding it and the current should be evenly distributed over the cathode circuits. The anode current measurements are shown in figure 8. Cathode placement inside the ground ring resulted in higher currents and therefore higher EOP system efficiency. Cathode measurements are plotted in figure 9. The back cathode current is nearly twice as high as the left and right side cathodes. This indicates that another cathode should be added to the back side to equalize the current distribution.

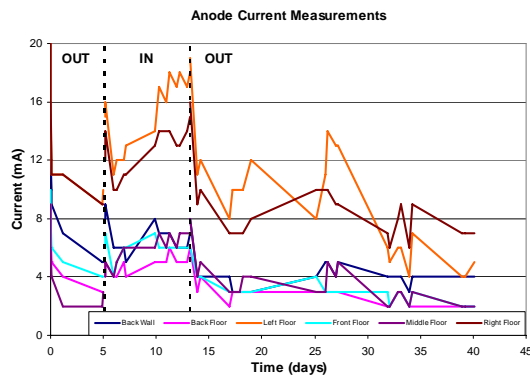


Figure 8: Plot of anode current vs. time for different cathode placements; INSide and OUTside the ground ring.

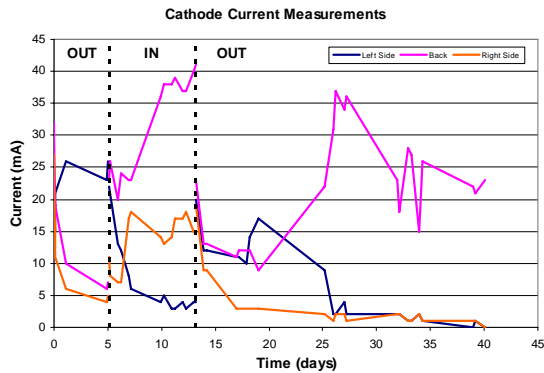


Figure 9: Plot of cathode current measurements vs. time for different cathode placements; INSide and OUTside the ground ring.

5.4 Potential for Hydrogen Gas Generation

A literature study was performed on the potential for hydrogen gas generation on reinforcing steel subjected to an electric field generated by the EOP system. According to literature, potentials more negative than -0.981 VSCE (voltage referenced to a

Saturated Calomel Electrode) are required in order to produce hydrogen gas. These potentials can be achieved only in the absence of oxygen. Since oxygen is reduced at potentials more negative than +0.247 VSCE, oxygen reduction is the preferred cathodic reaction under normal conditions. This is also shown in a potential-pH equilibrium diagram (Fig. 10) by Pourbaix (1966).

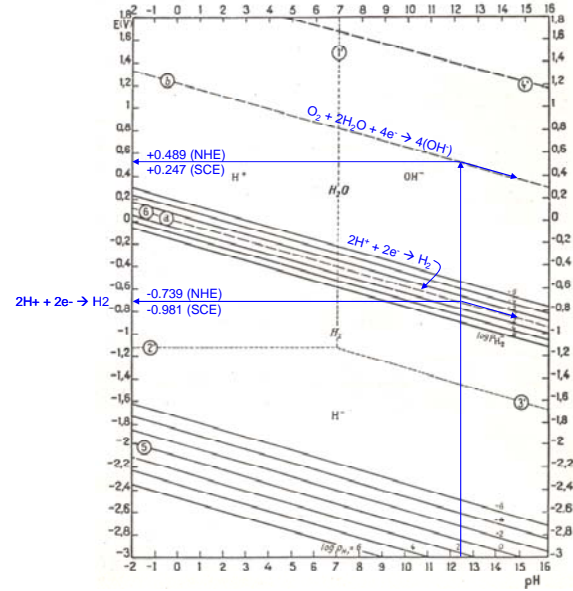


Figure 10: Potential-pH equilibria diagram for the system hydrogen-water, at 25°C.

If hydrogen were generated, then that hydrogen would be effectively destroyed (oxidized back to water) if it came in contact with the surface of any anode, or with any steel surface less negative than -0.981 VSCE within the concrete.

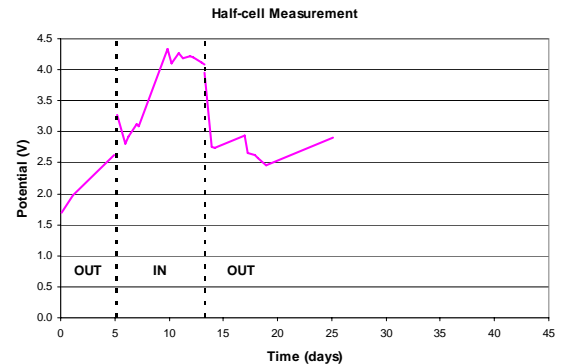


Figure 11: Plot of half-cell measurements vs. time for different cathode placements; INSide and OUTside the ground ring.

Figure 11 is a plot of the steel potential over time using a Cu-CuSO₄ half cell. Note that the potential reaches a steady state condition of around +4.25 VCSE and never goes negative. To convert the Cu-CuSO₄ (VCSE) potential measurements to VSCE measurements, 60 mV must be added to the VCSE values (ASTM, 2004). This results in a +4.31 VSCE steady state condition, well above -0.981.

5.5 DC Current Field Effects on Interior Material

EOP utilizes an electric field induced in the concrete to move water away from the anode side of a concrete surface. The field is created between the anode, buried in the concrete interior and the cathode, buried in the soil outside the structure. Objects not between the anode and cathode are only minimally affected by the current flow. However, the potential for current flow onto and through metal objects placed on top of a floor with EOP protection is not known. If the metal objects are tied to a ground it is not clear if current will flow from the floor, through the object and to the ground. A test was conducted in the model to monitor and measure current and voltage flow to simulated metal pallets on a concrete floor when they were both floating and tied to the structural ground. Two steel frames constructed from wire mesh were placed on the model floor and current and voltage potentials measured between them and the structure. They were then tied to the grounding system and the current and voltage potentials measured again.

The potential was measured between the two pallets and also between the pallet and the screws in the four corners of the ceiling. The current was found by measuring the potential across a 0.1 ohm resistor. The measured potential was 0.0 mV for the entire test period, indicating that metal pallets are not affected by the EOP system.

6. Concrete moisture

Concrete moisture data was collected with a Protimeter. The Protimeter measures the relative percent moisture concentration of the concrete at the depth the probes are placed. Three sets of probes were grouted into the floor section at a depth of approximately 1 inch. Because the steel half-cell measurement required adding moisture to the concrete, the moisture readings for all of the probe locations were 100% while potential measurements were taken. Figure 12 is a plot of the concrete subsurface moisture. Moisture content remained at 100% while the steel half-cell measurements were conducted. This is because water was added to the

system in order to carry out this measurement. When the steel half-cell measurement was discontinued the concrete began drying out.

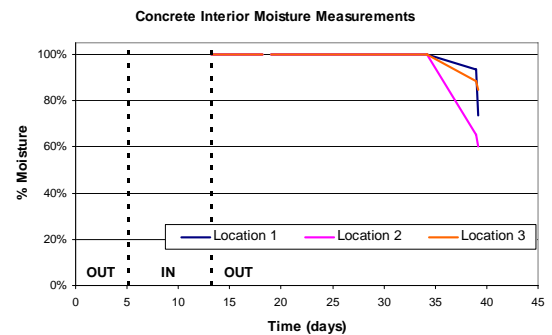


Figure 12: Plot of the percent moisture at 1-inch depth in concrete vs. time for different cathode placements; INside and OUTside the ground ring.

On day 13 of the test period, collection of surface moisture data was begun. Figure 13 is a plot of surface moisture indicating that the surface of the concrete on the interior of the model is drying out while the exterior is remaining wet.

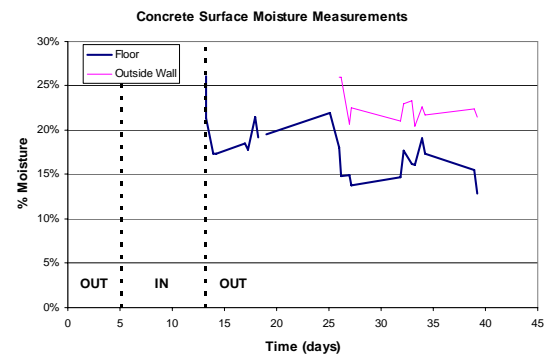


Figure 13: Plot of concrete surface moisture vs. time for different cathode placements; INside and OUTside the ground ring.

6. DISCUSSION

6.1 Sparking Potential Evaluation

Measurements to detect a differential build-up of electrical charge on the interior of the model indicated that a charge build up will not occur. Based on observations inside the magazines and on the construction drawings provided to ERDC-CERL, the interior steel arch of the magazines are electrically connected to the ground. As long as this ground is

achieved, there is no potential for differential charge build-up on the steel arch.

6.2 Lightning Protection System Evaluation

The experiments conducted in this study discovered no significant interfering effects between the lightning rod system and the EOP system in the model. There were no obvious indications that the systems will interfere.

Examination of the floor plans for the bunker indicates that interfering effects will likely be minimized if EOP cathodes are placed inside the foundation footing ground loop. The lightning current will tend to spread out into the surrounding earth away from the metal structure and the EOP system currents (anode-to-cathode) will not flow directly across the lightning protection ground ring.

6.3 Cathode Placement Evaluation

Laboratory experiments evaluating the effectiveness of the EOP system on cathode placement indicate that the cathodes need to be maintained inside the foundation footing ground loop.

6.4 Hydrogen Gas Generation Potential

An engineering study of hydrogen gas generation potential for an EOP system indicates that there is no potential for hydrogen gas generation. Half-cell potential measurements indicate that the voltage levels produced by the EOP system will only produce hydroxyl ions in the presence of water, raising the pH and further reducing corrosion potential for the steel reinforcing.

6.5 DC Current Field Effects on Interior Materiel

No electrical current was detected on the model steel pallets placed in the model. The electric current is directed away from the concrete surface toward the cathodes. As a result, there is no danger of current flowing onto the pallets or the materiel stored on them.

6.6 Concrete Moisture

As anticipated, moisture measurements of the concrete floors of the model showed a drying of the surface of the concrete while the deep cross-section of the concrete remained slightly wet. In saturated soil, the surface of the concrete adjacent to the soil will remain saturated, typically to the degree that the

soil is saturated. The EOP system will effectively keep the interior surface of the concrete relatively dry, typically less than 15-20 percent relative moisture.

7. PHASE II INVESTIGATIONS

Following presentation of the laboratory test results to the Fort A.P. Hill safety office, the Defense Ammunition Center/U.S. Army Technical Center for Explosives Safety and members of the DoD Explosives Safety Board, approval was obtained to install an EOP system in an 11-foot by 30-foot steel arch ECM at Fort A.P. Hill, Virginia. Figure 14 shows the interior of the ECM after the EOP system was installed. Figures 15 through 17 show various steps in the EOP system installation: Figure 15 shows the chipping operation for installing a 3/4-inch wide mixed metal-oxide coated titanium mesh anode at the wall-floor juncture; Figure 16 is a photograph of a cathode installed through the ECM floor; and Figure 17 shows the anode and associated lead wires being grouted in the floor of the ECM.



Figure 14: Interior of ECM with EOP installed.



Figure 15: Chipping of 1 1/2-inch deep groove for anode placement.



Figure 16: Cathode placement through the floor to the exterior of the ECM



Figure 17: Grouting of anode and lead wires in ECM floor.

Once the EOP system is activated, testing will be conducted to evaluate the potential for corrosion of the rebar, generation of a spark, and hydrogen generation. The ECM will be evaluated for reinforcing steel continuity and for radio frequency interference (RFI) and electromagnetic interference (EMI). The lightning protection system installed in the ECM will be tested to measure any interference that may be the result of the EOP system operation. This testing is scheduled to be completed by mid-November 2006.

Long term monitoring of the moisture in the concrete at select locations will be initiated. Moisture data will be collected at the surface and at depths of 3-inches, 6 inches and 9 inches within the concrete cross-section.

8. CONCLUSIONS

Laboratory testing on a model earth covered magazine was performed to evaluate the effects of EOP system operation on the integrity of the lightning protection system and the safety of

material. The performance of the EOP system was also evaluated. The conclusions of the EOP laboratory study are all favorable.

- There is no danger of a spark being generated by the EOP system.
- There is no significant interference between the EOP system and the lightning grounding system in the ECM.
- There is no detectable current flow onto metal objects stored inside the ECM with a functioning EOP system.
- The EOP system will dry the interior surface of the concrete in ECMs where it is installed.
- Optimum cathode placement for the EOP system was demonstrated to be inside the ground ring.
- Hydrogen gas generation by the EOP system is unlikely as the reinforcing steel potentials are always well above the generation potential.

Results of the laboratory study were presented to the Fort A.P. Hill safety office, the Defense Ammunition Center/U.S. Army Technical Center for Explosives Safety and members of the DoD Explosives Safety Board. Approval was given to proceed with installation of an EOP system in an 11-foot by 30-foot steel arch ECM at Fort A.P. Hill, Virginia.

ACKNOWLEDGEMENTS

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Thanks to OsmoTech for allowing use of the patented EOP pulse waveform.

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